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Indirect Field - Oriented Control of Induction Motor

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***Abstract*— The dynamics of the induction motor drive can be made independent of the position as well as speed control by using the field oriented control strategies. There are various techniques available under this category. One of such strategies is Indirect Field-Oriented Control method for the Induction motor drive. The speed control is observed in both, open-loop and closed-loop control applications. The speed regulation is achieved with a PI controller which converts the command speed into the command torque and therefore the speed of the drive.**

***Index Terms*—Induction motor, Indirect-Field Oriented Control, open-loop control, closed-loop control, slew rate, PI Controller.**

I. Introduction

THIS article aims at study of the simplest and least expensive speed control technique for induction motor drives. In the field oriented control strategy, nearly instantaneous torque control can be obtained allowing the drive to act as a torque transducer [1, 2, 3].

Although direct field-oriented control can be made fairly robust with respect to variation of machine parameters, the sensing of air-gap flux linkage is somewhat problematic and expensive in practice [1]. This motivated to develop indirect field-oriented control methods that are more sensitive to knowledge of the machine parameters but do not require direct sensing of the rotor flux linkages. In the field oriented control strategy, nearly instantaneous torque control can be obtained allowing the drive to act as a torque transducer.

The study involves two parts: the first, develop a current source invertor (CSI) with open-loop, and the second, a closed-loop control using PI controller. For this purpose, we used the data of a 50HP induction motor, the details of which are given in the TABLE I.

This article includes three sections. The first section includes design and development of a mathematical model for Induction motor with a CSI using Simulink and study the behavior or different parameters with the variation of electrical torque. The second section includes closed-loop speed control using a PI controller. The third section focuses on the behavior of induction motor by removing the limitor in the PI controller used in closed-loop control.

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TABLE I
DATA OF INDUCTION MOTOR

Symbol	Quantity	Value
P	Poles, P	4
HP	Capacity	50 hp
V	Voltage Rating	460 Volts
rpm	Speed	1705 rpm
T_m	Torque	198 N.m
I_B	Current (abc phase)	46.8 amp
r_s	Stator Resistance	0.087 Ω
$r_r j$	Rotor Resistance	0.228 Ω
X_{ls}	Stator Leakage Reactance	0.302 Ω
X_M	Magnetic Reactance	13.08 Ω
X_{lr}	Rotor Leakage Reactance	0.302 Ω
J	Inertia	1.662 kg.m^2

The rated voltage given here is 460V which is used to calculate the DC voltage used for the drive system and here the dc voltage is supposed to be 110% of the nominal voltage. Therefore we calculate it by using following formula

$$V_{dc} = \sqrt{\frac{2}{3}}\left(V_{rated}\right)\left(\sqrt{3}\right)\left(1.1\right) \approx 720V \tag{1}$$

II. A model for IFOC Control with CSI

A. Design of a Simulink model

To control the speed of the induction motor, it is necessary to achieve the controlled AC voltages. For this purpose, Hysteresis Modulation Technique is the most appropriate option [1, 4, 5]. Using this technique, we developed a current source invertor (CSI). This requires a constant DC voltage source and the AC input stator currents for three phases. The design of the CSI is as shown in the Fig. 1.

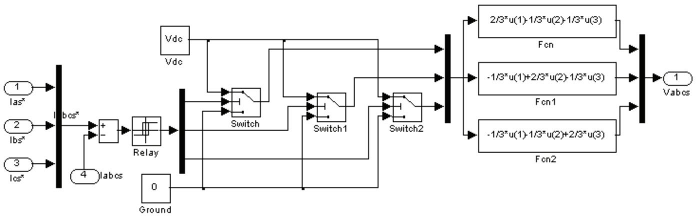

Fig. 1. Current Source Invertor Using Hysteresis Modulation Technique

The rotor angle, □ is derived from the electrical torque $\boldsymbol{T_e}$ and the d-axis rotor flux linkages $\boldsymbol{\lambda_{dr}}$. The equations for the current source invertor are as follows

$$i_{qs}^{*} = \frac{\left(\dfrac{4T_e^{*} L_{rr} P}{3L_m}\right)}{\lambda_{dr}^{*}} \tag{2}$$

$$i_{ds}^{*} = \frac{\lambda_{dr}}{L_m} \tag{3}$$

$$\theta = \int \left[\left(\frac{i_{qs}^{*}}{i_{ds}^{*}} \right) \frac{rr_2}{L_r} \right] + w_r \tag{4}$$

The model is developed in Simulink based on the above equations and s shown in the Fig. 2.

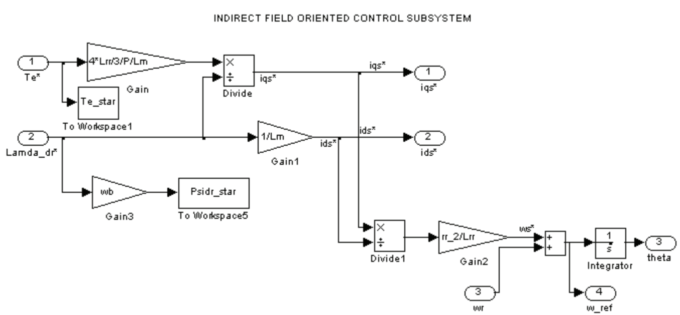

Fig. 2. IFOC for the induction motor drive

Also a model for the induction motor is developed based on the equations of torque, current and flux linkages between stator and rotor. Combining the designs shown in Fg. 1 and Fig. 2, with the Simulink model of induction motor, a complete model for the IFOC control of induction modtor is developed and as shown in the Fig. 3.

This complete model is then used to study the behavior of various parameters of the induction motor such as, *Vas_f*, i_{as}, i_{dc_f}, P_{dc_f}, ψ_m, Te, Tm, ω^{*}_{rm}, and ω_{rm}.

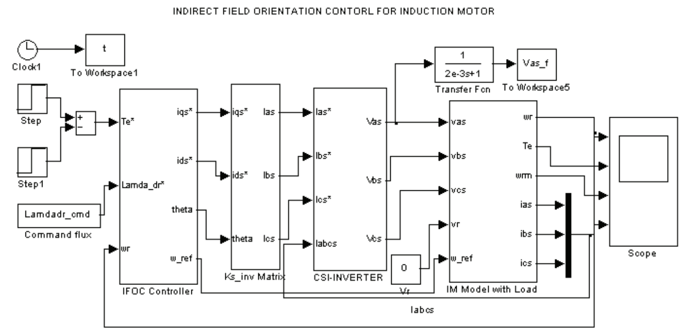

Fig. 4. Complete Model for IFOC control of Induction Motor using Simulink

A. Study of parameters using the IFOC controller

The drive system starts with zero initial conditions. At t=1.2s, step change the torque command to $T_e^{*} = 150\,N.m$. Then at t=2.0s step change the torque command to $T_e^{*} = -200\,N.m$. The Current Source Inverter with Hysteresis Modulation is used with current tracing error as: $\varepsilon = \pm 2.0$.

The different results obtained by running the model for the given specifications are as shown in the Fig. 5. and Fig. 6 below.

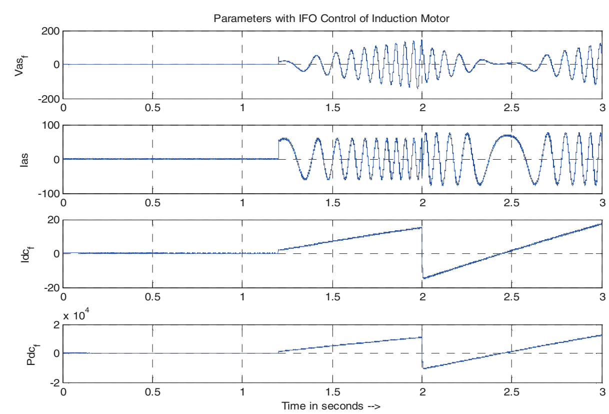

Fig. 5. Parameters of Induction Motor Drive using IFOC

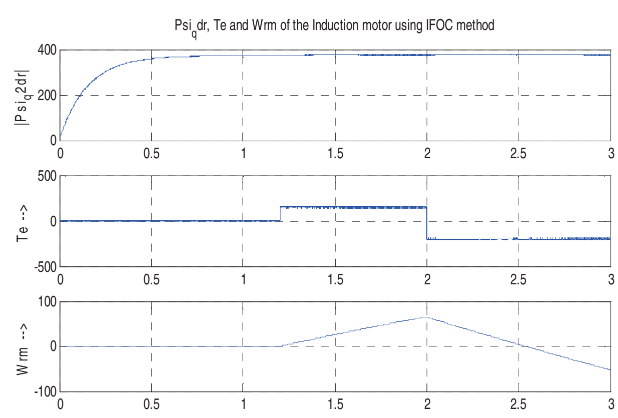

Fig. 6. Flux and the Modulation Index of the Drive system

B. *Observations and Conclusions*

It is possible to use the Field Oriented Control for the control of torque. Indirect Rotor Field-Oriented Control is applied to control the electromagnetic torque Te instantaneously with the torque command. With the application of positive torque, there are transients in the behavior of voltage and current. Whereas, at this moment i.e. at t = 1.2 seconds, the dc current increases linearly and hence the DC output power. Between t=1.2sec and t=2 sec amplitude and frequency of V_{asf} increase linearly. At the same time the rotor speed increases linearly till t=2 seconds. The rotor current reverses from time t= 2 seconds to t= 2.5 seconds with its frequency reducing further. From t= 2.5 seconds to t=3 seonds, the frequency of current and V_{asf} starts increasing. For a period of t= 2 seconds to t=2.5 seconds, the dc current and the output power are negative which indicate that the machine is in generating mode. This condition reverses from t= 2.5 seconds to t=3 seconds where the machine gain starts acting as a motor.

III. CLOSED LOOP SPEED CONTROL IN IFOC BY ADDING A PI CONTROL

In order to regulate the motor speed in a closed loop, we implement the PI controller which converts the command speed into the command torque and this command torque signal is then fed to the IFOC controller and consequently the speed of the motor is controlled. The model for this part remains the same as that of the previous one i.e. part (A) of the Part II except the new addition of the PI controller at the input of the IFOC controller. The Fig. 7 shows the design of the PI controller subsystem for this purpose.

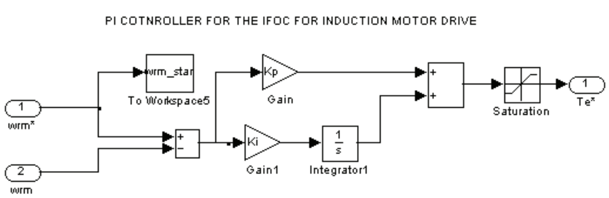

Fig. 7. Sub-system of PI Controller for the IFOC for Induction Drive

The initial conditions assumed here for the detailed study using PI controller are K_P = 150 and K_I = 10 K_P and the integral portion of the controller command is limited as well as the overall toreque command is limited to + and –ve 1.2T_b. The model is started with command rotor speed zero and then at t=1.2seconds, there is a step change of 100rad/seconds is fed to the controller and the model is allowed to run till t=3 seconds. The characteristics and the behavior of various parameters for this running condition are given in Fig. 8.

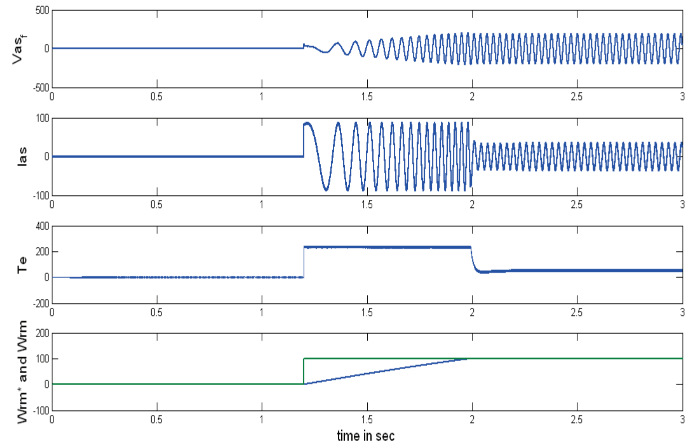

Fig. 8. Parameters of Induction Motor Drive using IFOC with PI controller

A. *Observations and Conclusions*

From the Fig. 8 above, it is observed that the voltage waveform shows the DC nature till t=1.2 seconds and after 1.2 seconds the frequency and amplitude of the V_{asf} goes on increasing till t=2 seconds after which it achieves the steady state value. The stator current shows the DC nature. The explanation for DC nature of the current is as follows

At t=0, the electrical command torque is zero. Therefore the command currents for the q-axis will be zero given by

$$i^{e*}{}_{qs} = 0 \tag{5}$$

Thus, we get the command slip speed as zero and given by

$$\omega^{*}{}_{s} = 0 \tag{6}$$

As the rotor speed is zero ($\omega_r = 0$), then the rotating velocity of the synchronous reference frame is zero i.e. $\omega_e = 0$. This means that the synchronous- reference frame is actually stationary.

As $\psi^{*}{}_{dre}$ is not zero, $i^{e*}{}_{ds}$ is not zero. Then

$$i_{cs} = i^{e*}{}_{ds} \tag{7}$$

$$i_{bs} = -i^{e*}{}_{ds} \tag{8}$$

and $i_{as} = 0$ (9)

Thus all the three phase currents are dc, with $i_{cs} = i^{e*}{}_{ds}$ and this is the reason why the stator current has DC nature before time t=1.2 seconds. At t= 2 seconds, the actual rotor speed ω_{rm} reached the command speed, therefore T_e reduced suddenly to the steady state value. Thus the magnitude of i_{as} decreased immediately.

IV. REMOVING THE LIMITOR IN THE PI CONTROLLER OF THE CLOSED LOOP SPEED CONTROL

Here for this part of the study, we removed the limits in the integral portion of the PI controller and assume all the initial conditions as well as other operating conditions to be same as that of SECTION III. The behavior of various parameters of Induction machine drive is as shown in the Fig. 9.

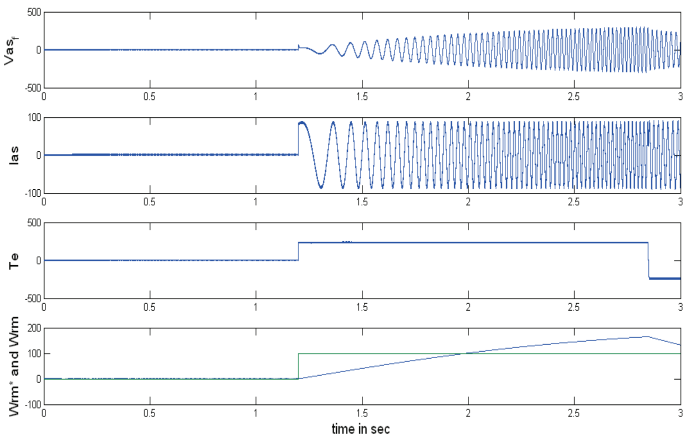

Fig. 9. Parameters of Induction Motor Drive using IFOC with PI controller but removing the limits in the integral portion.

A. Observations and Discussion

The behavior or the stator voltage, V_{asf} is same as that in the earlier section except here after time t = 2.8 seconds (approximately) it started reducing again with amplitude. While there was no change in the stator current as its amplitude remained the same after time t = 2 seconds but the frequency went on increasing after t= 2 seconds. The main observation was the difference in behavior of the rotor speed than from the previous case. Here the rotor speed continuously increased linearly after time t = 1.2 seconds and it continued even after t= 2 seconds till time t= 2.8 seconds (approximately). The speed started reducing after 2.8 seconds while the command speed is at the same value of 100rad/sec.

V. CONCLUSION

A. Effect of Limit in the PI Controller

The behavior of induction motor drive in both conditions, with and without application of limit on the PI controller is shown in the Fig. 8 and Fig. 9. A deliberate difference is seen in the behavior of parameters from these two figures. In absence of the limits, there was no control over the rotor speed (refer Fig. 9) where it is found that the rotor speed increased linearly even after time t = 2 seconds and then started decreasing after time 2.8 seconds. Whereas, by putting the limits, the rotor speed reached to the steady state value just at time t = 2 seconds (refer Fig. 8).

Thus we can say that, incorporating the limits in the integral portion of the PI controller, makes the steady state error in speed zero and there is stable operation of the motor which in turn improves the quality of operation of the motor as well as saves its life.

B. Advantages and Disadvantages over other speed control techniques.

The steady state speed error in the case of Part 2 is negligible. Compared to the other close loop control methods such as Voltage per Hertz control, Indirect Rotor Field Oriented control has faster speed response, less transient oscillations in terms of voltage, current, and torque. Therefore, it has higher performance and more advantages than close loop Voltage per Hertz control. The amplitudes of the transients are completely controlled by the IFOC method which is not possible by other methods such as Volt-per-Hertz Control. The speed control is smoother and better in the case of IFOC control.

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